REPORT OF THE WORKING GROUP ON METHODOLOGY FOR ASSESSMENT OF DEVELOPMENT POTENTIAL OF DEEPER AQUIFERS

METHODOLOGY FOR ASSESSMENT OF DEVELOPMENT POTENTIAL OF DEEPER AQUIFERS

Central Ground Water Board
Faridabad
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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The National Water Policy (2002) states that 'exploitation of ground water resources should be so regulated as not to exceed the recharge possibilities, as also to ensure social equity'. The amount of water which is replenished annually through rainfall and other sources like irrigation etc is known as the replenishable ground water. The annual replenishable ground water resources of the country has been estimated as on 2004 based on the methodology of Ground Water Estimation Methodology (GEC-1997). Attempt has also been made to categorize the assessment units into different categories as per the stage of development and water level trends.

The present scenario of annual replenishable ground water resources is not very encouraging as nearly 18% of the assessment units in the country have been placed under over exploited/ critical category. Out of 5723 blocks/ taluks/ mandals, 839 are over-exploited and 226 are critical. The overall stage of ground water development in some of the states like Delhi, Haryana, Punjab, Rajasthan, UT of Daman & Diu & Pondicherry has already exceeded 100% and in Gujarat and Tamil Nadu, it is between 75 to 100%.

Over-exploitation of ground water resource (stage of ground water development - more than 100%) refers to the development of ground water resource which is available below the active recharge zone or zone of fluctuation that is sometimes referred as Static or In–storage ground water reserve. Hence, in addition to the annual replenishable ground water resource, there exists a huge ground water reserve in the deeper aquifers below the active recharge zone and in the confined aquifers in the areas covered by alluvial sediments of river basins, coastal and deltaic tracts constituting the unconsolidated formations. The present attempt is towards establishing a methodology for assessment ground water potential of deeper aquifers below the first confining layer in the alluvial areas.

1.2 COMPOSITION OF THE WORKING GROUP

In view of dwindling fresh water sources, ever-growing requirements and increasing dependence on ground water, necessity has been felt to assess the potential and scope of ground water development of deeper aquifers especially in the multi-aquifer systems in the alluvial areas. In this context R&D Advisory

Committee on ground water estimation constituted a Working Group to recommend the methodology for estimation of development potential of deeper aquifers. Constitution of the Working Group is as follows –

1.	Member (SAM), CGWB	Chairman
2.	Chief General Manager, NABARD	Member
3.	Representative from Ground Water Cell, Directorate of Agriculture, Govt. of Haryana	Member
4.	Representative from Water Resources & Environment Directorate, Irrigation Department, Punjab	Member
5.	Representative from State Ground Water, Department, Uttar Pradesh	Member
6.	Sujit Kr. Sinha, Scientist 'D' CGWB	Member
7.	Rana Chatterjee, Scientist 'D', CGWB	Member Secretary

1.3 TERMS OF REFERENCE

The terms of reference of the working group are as follows –

1. To review the scientific studies carried out with respect to the confined (deeper) aquifer.
2. To suggest suitable methodology to assess the development potential of deeper aquifers.
3. To review the status of utilization of deeper aquifer.
4. Any other aspect relevant to the terms referred above.

1.4 PROCEEDINGS OF THE WORKING GROUP

The Working Group held three meetings during which in-depth discussions were held within the ambit of the terms of reference. The working group decided that the scope of the present study would be restricted to the first confined aquifer. Pilot studies in this regard were initiated in identified areas in Haryana & Punjab states. The areas identified for the study in Haryana are Yamunanagar, Kurukshetra, Karnal and Panipat districts and in Punjab is Bist Doab comprising of Hoshiarpur, Jalandhar, and Kapurthala districts. The various data utilized for the purpose of sample computations including the parameters related to aquifer geometry of the first confined aquifer has been jointly reconciled by CGWB with the respective state government agencies.

In order to finalize the report of the Working Group, a sub-committee was formulated with the following members –

1. Sanjay Marwah, Scientist ‘D’, CGWB
2. Rana Chatterjee, Scientist ‘D’, CGWB
3. S. K. Sinha, Scientist 'D', CGWB

The copies of the official orders regarding constitution of Working Group and Sub-committee for report writing are given as Annexure 1.

CHAPTER 2

GROUNDWATER SCENARIO OF DEEPER AQUIFERS

2.1 HYDROGEOLOGICAL SETUP

Two broad groups of water bearing formations have been identified in the country depending on occurrence and movement of ground water Viz. *Porous Formations* which can be further classified into unconsolidated and semi consolidated formations having the primary porosity and *Fissured Formation* or Consolidated formations which has mostly the secondary or derived porosity. The major aquifer systems and their yield prospects are shown in **fig.1**.

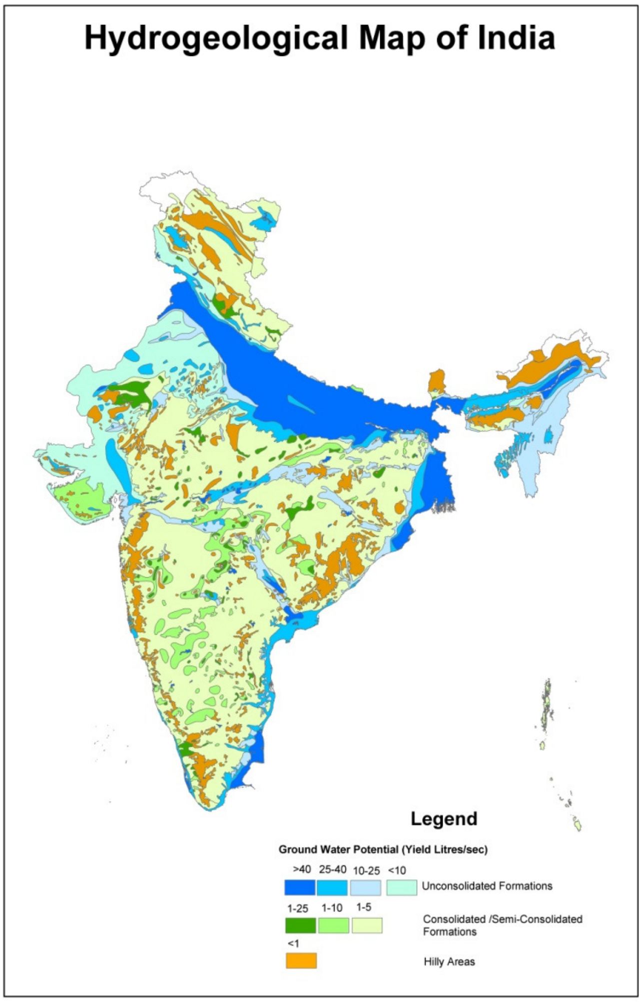
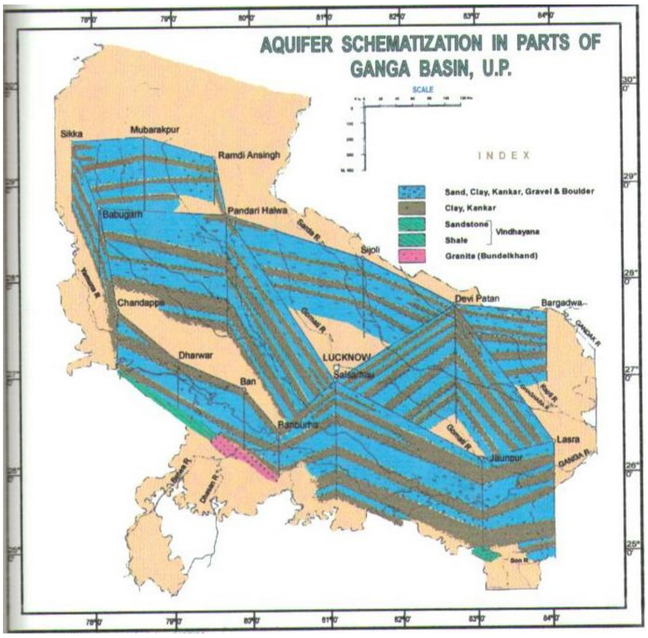


Fig 1 Hydrogeology of India

In India prolific deeper aquifers exist in Indo-Gangetic-Brahmaputra basin and Coastal tracts. Deeper aquifers with relatively good potential also exist in the faulted basins in Godavari, Mahanadi, Narmada, Tapi, Son and Damodar basins. Hard rock terrains are comparatively devoid of high potential deeper aquifers.

Indo-Gangetic-Brahmaputra Alluvial Plains

This region encompasses an area of about 850,000 sq km covering states of Punjab, Haryana, Uttar Pradesh, Bihar, Assam and West Bengal, accounting for more than one fourth of country's land area, comprises the vast plains of Ganges and Brahmaputra rivers and are underlain by thick piles of sediments of Tertiary and Quaternary age. This vast and thick alluvial fill, exceeding 1000 m at places, constitute the most potential and productive ground water reservoir in the country. These are characterized by regionally extensive and highly productive multi-aquifer systems. The deeper aquifers available in these areas offer good scope for further exploitation of ground water with suitable measures. In Indo-Gangetic- Brahmaputra plain, the deeper wells have yield ranging from 25-50 lps. Aquifer schematization in parts of Ganga basin are depicted in figures 2.



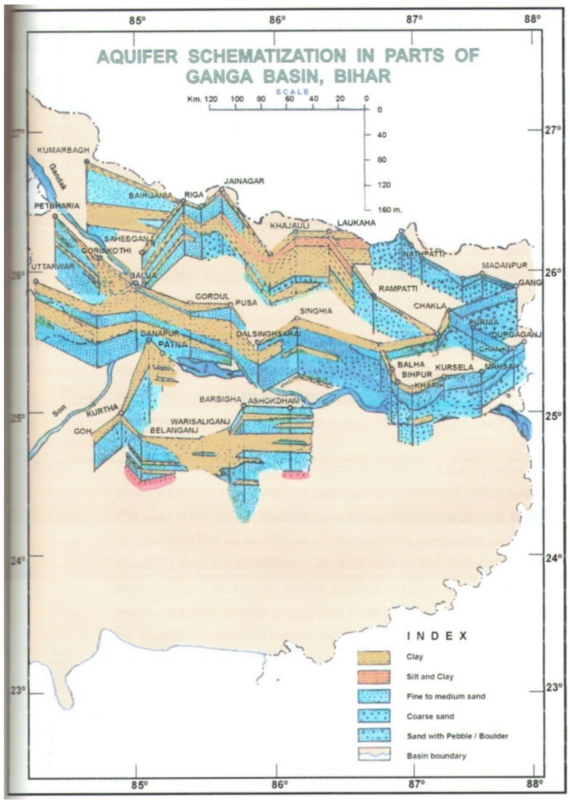


Figure 2: Aquifer schematization in parts of Ganga basin

Coastal Area:

India has a main land coastal tract of about 5400 kms. characterized by thick cover of alluvial deposits of Pleistocene to Recent age and constitutes potential multi-aquifer systems in the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Orissa and West Bengal. Ground water prospects and yield potential in these aquifers vary widely depending on the local conditions. However, inherent quality problems and the risk of seawater ingress impose severe constrains in the development of these aquifers.

Aquifers along the coastal tracts of India can be broadly classified as aquifers in porous sedimentary formations and in fissured formations or the hard rock aquifers. The sedimentary tracts, all along the east coast and the coastal plains of Kerala and Gujarat are mostly occupied by 'porous' aquifers while major parts of west coast and parts of Andhra Pradesh and Tamil Nadu coasts are occupied by 'fissured' aquifers. Further the aquifers in the sedimentary tract can be grouped depth-wise into two main groups, viz. shallow aquifers, mostly in the Quaternary alluvium and deeper aquifers in underlying sediments ranging in age from Tertiary to Permo-Carboniferous. Shallow aquifers are mostly separated from underlying deeper aquifers by clay layers. In coastal areas, the aquifers comprising of saline and fresh water represents varied conditions in terms of their dispositions. Some of the typical examples of saline-fresh water interface for the state of Gujarat, Andhra Pradesh and West Bengal are shown 3a, 3b, 3c respectively.

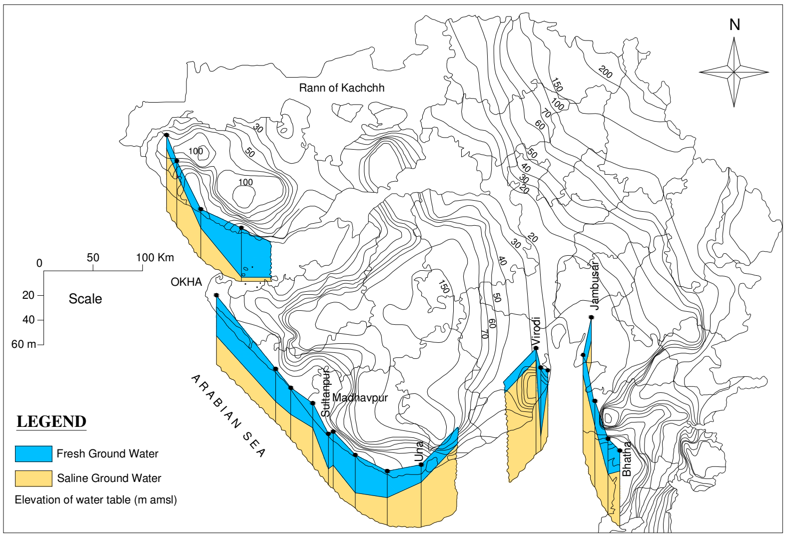


Fig 3a: Fresh-Saline interface along coastal Gujarat

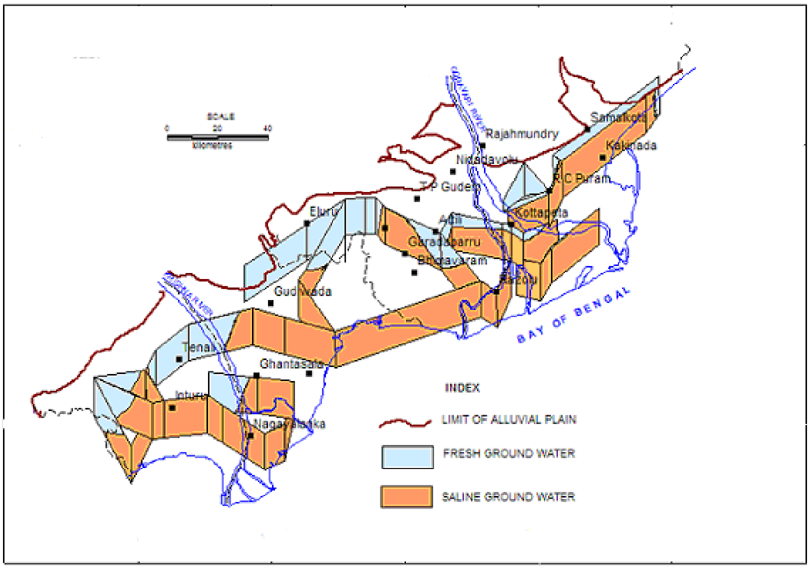
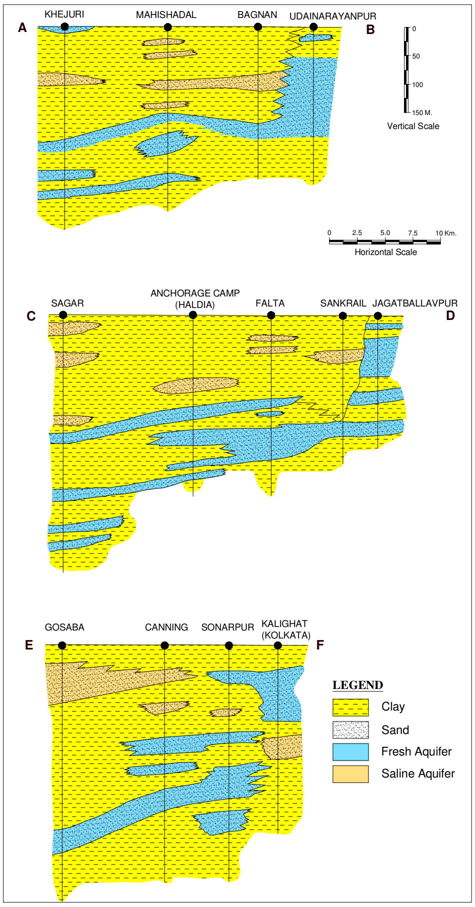


Fig 3b: Fresh – Saline ground water interface, Krishna – Godavari Plains, AP



Fresh - Saline aquifers along selected sections, West Bengal

Peninsular Shield area and faulted basins

The peninsular shield areas consist mostly of consolidated sedimentary rocks, basalts and crystalline rocks in the states of Karnataka, Maharashtra, and Tamil Nadu, Andhra Pradesh, Orissa and Kerala. Occurrence and movement of ground water in these areas is restricted to weathered residuum and interconnected fractures having limited ground water potential. Ground water occurs mainly in the weathered and fractured zones of rocks, within depth of less than 50m, occasionally down to 100m. In these areas, due to absence of multilayered aquifers and practically non- existence of secondary porosity at depths more than 100m, chances of deeper potential aquifers is remote.

Faulted / structurally controlled basins in peninsular India having unconsolidated, semi-consolidated and consolidated formations have ground water potential in deeper aquifers under favourable hydrogeologic situations. In Godavari, Mahanadi, Narmada, Son and Damodar basins, ground water occur in sedimentary formations. The total thickness of the sediments is extent upto 7000 m. These sedimentary strata under suitable topographic conditions, give rise to auto flowing conditions in wells. Extensive valley fill deposits exist in three discrete fault basins - the Narmada, the Purna and Tapi valleys. The thickness of valley-fill deposits ranges in thickness from about 50 to 150 m.

2.2 STATUS OF GROUND WATER DEVELOPMENT

Ground water withdrawal for various uses and evapotranspiration from shallow water table areas constitute the major components of ground water outflow. In general, the irrigation sector remains the main consumer of ground water. Data available from the census of minor irrigation schemes (Table.2) indicates a three-fold increase in the number of ground water abstraction structures from about 6 million during 1982-83 to about 18.5 million during 2001-02 (Fig.4).

Table.2 Growth of Ground Water Abstraction Structures in India

Type of Structure	Number of Structures			
	1982-1983	1986-1987	1993-1994	2000-2001
Dug well	5384627	6707289	7354905	9617381
Shallow Tube well	459853	1945292	3944724	8355692
Deep Tube well	31429	98684	227070	530194

As per the definitions given in 3rd Minor Irrigation Census, dug wells are open wells, shallow tubewells are upto 60 to 70 meters deep and deep tubewells extends beyond 70 m in depth. Thus, the census of tubewells are with respect to depth and not with respect to aquifer.

It is also seen that the growth has been more pronounced in shallow and deep tube wells (17 to 18 times) when compared to dug wells (about 2 times). This shift is probably the combined result of deepening ground water levels and advances in drilling and pumping technology.

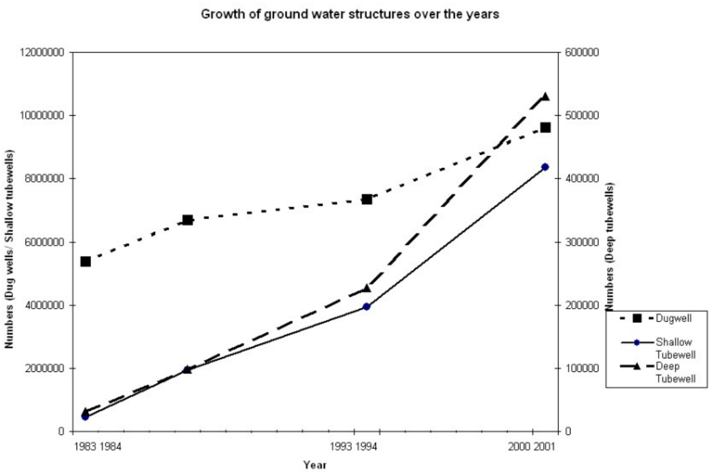


Fig.3:- Growth of Ground Water Abstraction Structures in India (Source: Minor Irrigation Census, 2001)

In most of the alluvial plains, ground water exploitation is presently from shallow aquifer. However in parts of Haryana, Punjab and Uttar Pradesh farmers are pumping ground water from deeper aquifers recently due to declining water levels, reducing well yields and assured ground water supply for future. At places, Public health department of state governments are also constructing pumping wells for drinking water supply from multiple aquifers including the deeper confined aquifer too. Recent studies conducted by NABARD in the selected blocks of Sangrur and Rupnagar districts of Punjab regarding sustainability of ground water use also revealed that – replacement of shallow tube well with deeper wells and centrifugal pumps with submersible pumps are common phenomena in the state. However, estimation of ground water utilization from deeper aquifers is not possible with the existing database, since census data provides informations regarding number of wells do not provide specific informations regarding aquifers being tapped.

CHAPTER 3

REVIEW OF RELATED STUDIES

Several studies have been conducted on the development and management of ground water resources of deeper aquifer systems in various parts of the world. Similar water balance studies were also carried out in India to decipher the ground water potential of the aquifer systems including deeper aquifers eg. Rajasthan and Gujarat (UNDP project), Upper Yamuna basin studies, Betwa river basin project etc. However no specific literature on methodology for assessment of development potential of deeper aquifer is available. In this chapter, two representative case studies – one each from India and aboard are illustrated.

1. GROUND WATER STUDIES - RAJASTHAN AND GUJARAT, INDIA

A bilateral project on water balance entitled 'Groundwater surveys in Rajasthan and Gujarat' was carried out during 1971 to 1974 by CGWB and UNDP with an objective to evaluate the ground water potentials and ground water quality. The detailed study including the assessment of development potential of deeper aquifer was mainly carried out in about 11000 sq. km. of part of the Gujarat plain in Mehasana district and parts of Banaskantha districts. The salient findings of the study as follows:

- The area consists of two major aquifer systems upto the explored depth of 600 m. The upper unit is mostly phreatic but becomes semi-confined to confined in some parts of the area consisting of relatively coarse grained sediments.
- The lower unit representing a confining condition comprises a few hundred meters of alternating sandy and clayey beds. The Aravalli foothill belts in the north-east of the area constitute principle recharge zones of the aquifer systems. The depth to the top of first confined aquifer varies from 78 to 162 metres. The thickness of this layer ranges from 10 to 80 m. The maximum thickness has been encountered in the central part of the area.
- The well and aquifer characteristics of the confined aquifer were determined through pumping tests. Specific capacity ranges from 1.8 $m^3/h/m$ to $49m^3/h/m$. Transmissivity (T) was found to be between 47 m^2/day and 3400 m^2/day. Most of the T values are between 200 to 600 m^2/day. Storage coefficients range from 0.6 to 12.3 * 10^{-4}.
- The annual ground water increment to the confined aquifers was computed on the basis of transmissivity and hydraulic gradients in the north-eastern zone where the phreatic and confined aquifers merge. The annual volume of replenishment of the confined aquifers thus obtained is 70 MCM.

- Mathematic model was applied to solve problems related to a multi-layer aquifer system, with leakage between layers in a part of the area and a zone in which the aquifer is not sub-divided called ‘common zone”.
- It was found that deeper confined aquifers do not show good prospect for development because of variable water quality, low transmissivity and low specific capacity of wells and considerable drilling depth upto 580 m. More-over influence of pumping from first confined aquifer have been noted in lower confined aquifers because of leakage between these aquifers.

2. DAKOTA AQUIFER SYSTEM, KANSAS, USA

Dakota aquifer systems are confined aquifers in southwestern Colorado and central and western Kansas, USA. It is mostly sandstone bounded on the top and bottom by regional aquitards consist largely of shale. The salient features of the Dakota aquifer systems are as follows:

- In the central Great Plains, the ground-water flow system in the Dakota aquifer is influenced primarily by regional and local topography and the Upper Cretaceous aquitard. The resultant ground water flow is on easterly direction across the region in all of the aquifer systems. The regional flow models have shown that the aquitard restricts the downward movement of recharge to the Dakota to near negligible levels.
- Hydraulic conductivities and specific storage of the aquifer have been found out through pumping tests and lab tests. The hydraulic conductivity data from the field hydraulic testing range from 3.6-88 ft./day with a geometric mean value of 12.5 ft/day and values of specific storage range from 1.5 x 10^{-7} (inverse feet) up to 2.9 x 10^{-5} (inverse feet), with a geometric mean of 2.1 x 10^{-6} (inverse feet). However, away from the basin center in Kansas and southeastern Colorado, the Upper Cretaceous aquitard thins from more than 2,000 ft in northwest Kansas toward its extent in central and southwestern Kansas. As a result, its control on the flow system in the Dakota aquifer diminishes toward the outcrop/ sub-crop belt.

- Only about 10% of the infiltrated water entering the aquifer moves downdip from the recharge area south of the Arkansas River into the confined Dakota in western Kansas and southeastern Colorado. Within the confined aquifer, the ground-water moves slowly northeastward towards the regional discharge area in central Kansas due to low aquifer transmissivity. Over most of western Kansas, the vertical hydraulic conductivity of the overlying Upper Cretaceous aquitard is very low, on the order of 1 x 10^{-7} ft/day or less. Freshwater recharge to the confined Dakota is negligible, less than 0.1% of the lateral flow within the aquifer. Most of the freshwater recharge to the confined Dakota enters where the aquitard is relatively thin and dissected near the outcrop/subcrop areas. Here, the vertical hydraulic conductivity is two to three orders of magnitude higher and recharge from overlying sources may amount to as much as 10% of the lateral flow within the aquifer. In central Kansas, an additional source of recharge to the Dakota comes from the underlying Cedar Hills Sandstone where both aquifers are hydraulically connected. The total recharge from this source amounts to less than 1% of the lateral flow in the upper Dakota aquifer.

- Computer simulations of the steady-state flow system indicate that the flux of fresh water through outcrop/subcrop belt is at least four times higher than in the confined aquifer to the west. In the Washington County area, the annual recharge to the Dakota is estimated to be on the order of 0.25 inches where it is unconfined. As a result, fresh and saline water springs and seeps can be found in the river valleys.

Computer simulations to assess the effects of pumping have demonstrated that in the confined upper Dakota aquifer, coalescing cones of depression from multiple pumping wells spaced from 1 to 4 mi apart form quickly after pumping begins. After 10 yrs, larger drawdowns than would be expected from a single pumping well are produced and a much larger area of the aquifer is affected by the withdrawals. Taking into account the heterogeneity of the Dakota, a well spacing of 20 miles in an east-west direction and 5 miles in a north-south direction is recommended to avoid mutual interference problems is affected by the withdrawals.

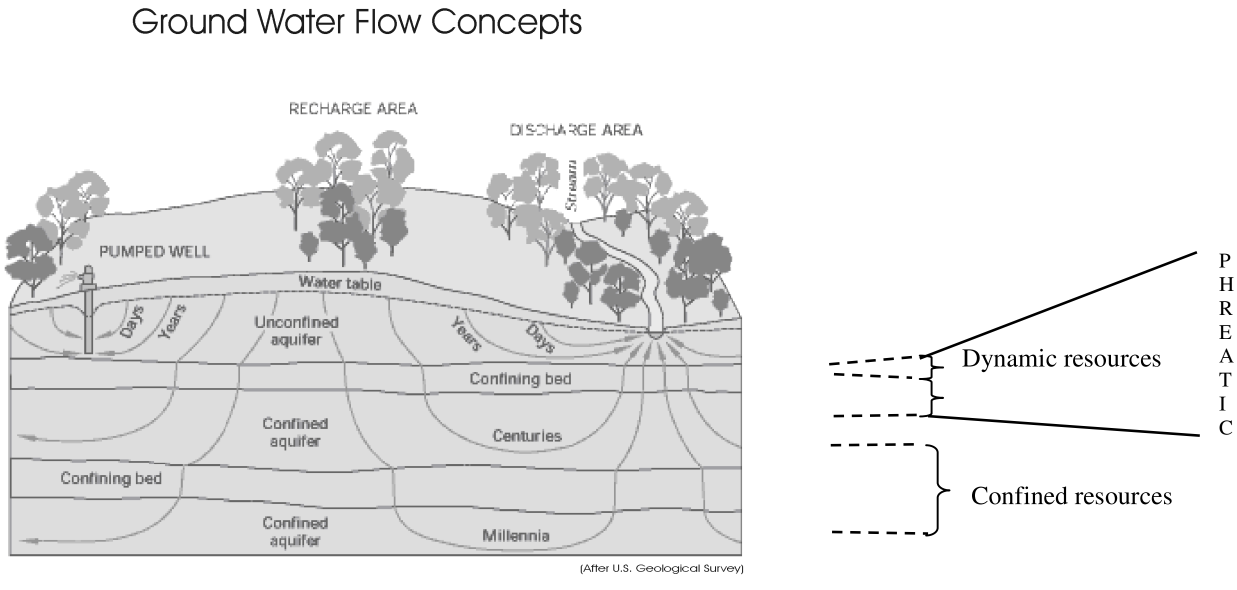
Concept of sustainable yield in Dakota aquifers

Sustainability of the Dakota Aquifer is the ability of the aquifer to supply water to users without being depleted during the planning period. As a practical matter, the planning horizon has been set to be for 20 yrs. Sustainability implies the attainment of a new dynamic equilibrium under conditions of widespread development. For equilibrium to occur withdrawals from the aquifer must induce either additional recharge to the aquifer, reduced discharge from the aquifer, or both. This occurs by increasing the hydraulic gradient into the aquifer when the hydraulic head within the aquifer is decreased. These decreases will continue until changes in recharge and discharge balance withdrawals from the aquifer. The most direct evidence of this new balance is long-term stability of hydraulic heads in the aquifer. The sustained yield depends on the rate at which the hydraulic head decreases propagate through the aquifer to the recharge or discharge area. The closer the pumping centers are placed to either the recharge or discharge areas, the more likely it is that additional recharge or reduced discharge can be realized by withdrawals. The rate of propagation is a function of aquifer diffusivity (the ratio of the hydraulic conductivity and the specific storage). The higher the diffusivity, the faster the rate of propagation and the more likely it will be that pumping centers located farther away from either the recharge or the discharge areas will influence the amount of recharge and discharge.

CHAPTER 4

METHODOLOGY FOR ASSESSMENT OF DEVELOPMENT POTENTIAL OF DEEPER AQUIFERS

Based on the occurrence, movement, and mechanism of release of ground water, the geologic material can be classified into various aquifer systems such as unconfined, semi-confined & confined. The groundwater which is available in the zone of water level fluctuation is called ***dynamic groundwater resources*** *or* annual replenishable groundwater resources. Below the zone of water table fluctuation, the groundwater which is available in the perennially saturated portion of the aquifer in the phreatic zone is called as ***static or in-storage groundwater resources****.* The water bearing formation below the phreatic zone has been considered as Deeper aquifer in the present context. The deeper aquifer broadly constitutes the Semi-confined and confined aquifers depending upon the nature and extent of the confining layers. The scope of the present study is to review various methodologies for assessment of development potential of first confined aquifer in the Deeper zone. The conceptual diagram depicting various aspects of ground water flow and aquifer systems is presented in figure 5.



The dynamic as well as in-storage ground water resources belongs to the unconfined / phreatic aquifer, the thickness of which varies from place to place depending upon depositional history. For computing dynamic ground water resources and Static ground water resources, detailed methodology has been outlined in the GEC-1997. An attempt has been made in this report to recommend the suitable method/s for assessment of resource potential of the first confined aquifer in the Deeper Zone.

4.1 METHODOLOGY FOR ASSESSMENT OF GROUND WATER POTENTIAL OF CONFINED AQUIFERS

A confined aquifer is broadly a porous and permeable geological unit, which is sandwiched between two relatively low permeability layers (Unconfined aquifers are only bounded by a low permeability layer below). Because the confining layers above and below these aquifer systems are usually regionally extensive, the recharge and discharge areas of these aquifers may be hundreds of kilometers apart. The ground water flow dynamics in confined aquifer is different from that in unconfined aquifer. The main source of recharge to any aquifer is rainfall. In case of unconfined aquifer, recharge is both through vertical infiltration and lateral inflow while in confined aquifer, the recharge is through lateral inflow and vertical exchange from top as well as bottom aquifers. The recharge zone in case of confined aquifer is located far apart and the ground water is under pressure. Under pre-development conditions within a confined aquifer, there is a dynamic equilibrium between recharge and the discharge or outflow from an aquifer. There is also water under pressure within aquifer and the total volume in storage remains relatively constant.

Confined aquifer systems are more sensitive to development than unconfined systems because of their hydraulic properties. In the wells tapping the confined aquifers, initially the water is released from the well storage and subsequently from the compressibility of the fluid and compaction of aquifer material which is controlled by elastic properties of aquifer material. However, in case of unconfined aquifer the mechanism of release of water is mainly because of desaturation of aquifer. The quantity of ground water involved in storage change in confined aquifers is usually several orders of magnitude smaller than that involved in phreatic aquifers (Karanth, 1987).

Assessment of development potential of confined aquifers assumes crucial importance, since over-exploitation of these aquifers may lead to far more detrimental consequences that those of shallow unconfined aquifers. If the piezometric surface of the confined aquifer is lowered below the upper confining layer so that desaturation of the aquifer occurs, the coefficient of storage is no longer related to the elasticity of the aquifer but to its specific yield. In view of the small amounts of water released from storage in the confined aquifers, large scale pumpage from confined aquifers has caused declines in piezometric levels amounting to over a hundred metre and subsidence of land surface posing serious geotectonic problems.

There are several methods mentioned in the literature on the assessment of ground water potential in confined aquifers. The most widely used analytical techniques are based on lumped approach using flow-rate and storage concepts. Numerical modeling techniques are commonly used at local to sub-regional scale using ground water flow equations.

a) Ground water flow rate concept

The rate of ground water flow in a confined aquifer in the area can be estimated by Darcy's law as follows:

Q = TIL

Where,

Q = Rate of flow through a cross section of aquifers in m^3/day

T = Transmissivity in m^2/day

I = Hydraulic gradient in m/km

L = Average width of cross section in km.

It is worthwhile to mention here that rate of flow arrived using the above equation is the ground water potential available in the specified space and time domain. While assessing the rate of flow in a defined boundary of confined aquifer, leakage from overlying and underlying aquifers need to be accounted for in the computations.

b) Ground water Storage concept

The co-efficient of storage or storativity of an aquifer is defined as the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in head. Hence the quantity of water added to or released from the aquifer (ΔV) can be calculated as follows

$$\Delta V = S\,\Delta h$$

If the areal extent of the confined aquifer is A then the total quantity of water added to or released from the entire aquifer is

$$Q = A\,\Delta V = SA\,\Delta h$$

Where

Q = Quantity of water confined aquifer can release (m^3)

S = Storativity

A = Areal extent of the confined aquifer(m^2)

Δh= Change in Piezometric head (m)

Most of the storage in confined aquifer is associated with compressibility of the aquifer matrix rather than compressibility of water. Once the peizometric head reaches below confining bed, it behaves like an un-confined aquifer and directly dewaters the aquifer. The quantity of water released in confined aquifer due to change in pressure can be computed between piezometric head (h_t) at any given time 't' and the bottom of the confining layer (h_o) by using the following equation.

$$Q_p = SA\Delta h = SA\,(h_0 - h_t)$$

Where
Q_p = Quanity of water under pressure(m^3)
S = Storativity
A = Areal extent of the confined aquifer(m^2)
Δh = Change in Piezometric head (m)
H_t = Piezometric head at time t
h_0 = Bottom of the Confining Layer

The storativity can be computed either by long duration pumping tests or by using the Jacob equation.

$$S = \theta\gamma b\beta\left(1 + \frac{\alpha}{\theta\beta}\right)$$

Where

S = Storativity
θ = porosity of the aquifer (fraction)
γ = Specific weight of water Kg/m^3
b = Thickness of aquifer (m)
β= The bulk modulus of compression of water (or reciprocal of the bulk modulus of elasticity) m^2/kg.
α = Bulk modulus of compression of the solid skeleton of the aquifer m^2/kg.

While assessing the ground water potential by flow rate and storage concept, the study area needs to be distributed into smaller units (zones) for accommodating the anisotropy in aquifer parameters (T & S) as well as spatial variations in piezometric heads. In case of piezometric heads, it is desirable to prepare the contours for pre and post monsoon periods separately so as to calculate the flow direction, length of flow as well as the hydraulic gradient. The hydraulic gradients should be preferably computed at optimal number of discrete points to arrive at average gradient for the entire area.

As far as possible the lowering of piezometric head below the upper confining layer to avoid any environmental degradation such as land subsidence and irreversible aquifer damage etc.

c) Ground water modeling concept

Ground water modeling technique is one of the advanced methods for assessment of ground water potential of confined aquifer. The methodology involves solving the governing differential equations of ground water flow either by Analytical or Numerical approach.

- ***Analytical Technique***

Analytical models attempts exact solutions to equations which describe very simple flow or transport conditions by lumped approach which is a closed form solution. Lots of assumptions are involved for simplification of the equation. Response is estimated for known excitation. Can be solved using simple calculations.

$$d/dx(T_{xx}\, dh/dx) + d/dy(T_{yy}\, dh/dy) - W = S\, dh/dt$$

where,

T_{xx}, T_{yy} are transmissivity along x, y coordinate axes; h is the hydraulic head; W is the flux term that accounts for pumping, recharge or other sources and sinks; S is the storativity; t is time.

Assuming,

One dimensional flow, Homogeneous aquifer, W is independent of x

The above equation changes to

$$d^2h/dx^2 = W/T \text{ (constant)},$$

by differentiating twice,

$$h = W/T * x2 / 2 + Ax + B$$

where, A & B are boundary conditions

and finally, after solving for the boundary conditions, the equation changes to

$$h = H_1 - \{(H_1-H_2)/L\}* x - W*x/2T * (L - x)$$

where, H_1, H_2 are the boundary conditions separated by a distance L and x is the distance between H_1 and the point at which head (h) is being calculated.

The above equation can be used to determine permissible level of pumpage, so that piezometric head should not go below the upper confining layer of the confined aquifer or to a defined level as must be the case. The minimum and maximum permissible pumpage can also be fixed by solving the equation with respect to 'x' and equating to zero.

Because of the simplifications inherent with analytical models, it is not possible to account for field conditions that change with time or space. This includes variations in groundwater flow rate or direction, variations in hydraulic or chemical reaction properties, changing hydraulic stresses, or complex hydrogeologic or chemical boundary conditions. Analytical models are best used for

- Initial assessments where a high degree of accuracy is not needed,
- Prior to beginning field activities to aid in designing data collection,
- To check results of numerical model simulations, or
- Where field conditions support the simplifying assumptions embedded in analytical models.

The Theiss, Theisms, Jacobs, Boultons method for analysis of pumping test data are good examples of analytical solutions of the radial flow equations. Similar analytical solutions are also available for different aquifers in Cartesian coordinates as discussed above, which provides closed form solutions between excitation and response. Under simplifying assumptions, these analytical solutions are very useful tool to determine permissible level of pumpage to maintain certain minimum water level / piezometric heads and assist in decision making or to test various other management options.

- ***Numerical Technique***

When the system is complex, anisotropy is to be considered, the only choice left is to go for Numerical Models which involves simulation of ground water flow equation in the specified spatial and time domain using discrete approach. Modeling technique requires enormous data and true demarcation of aquifer geometry which may not be practical for regional aquifer system. However, ground water flow models can be simulated for a smaller study area which requires proper planning for data collection. The results of such studies can be extended to other areas with similar hydrogeological conditions.

Numerical models are capable of solving the more complex equations that describe groundwater flow and solute transport. These equations generally describe multi-dimensional groundwater flow, solute transport, and chemical reactions. The commonly used numerical approaches used in practice today for solving ground water flow equations are Finite Difference Method (FDM) and Finite Element Method (FEM) , other than that some latest models also uses Method of Characteristics (MOC) as well.

The accuracy of model predictions depends upon the degree of successful calibration and verification of the model simulations. Errors in the model used for predictive simulations, even though small, can result in gross errors in solutions projected forward in time. Monitoring of hydraulic heads and groundwater chemistry (performance monitoring) will be required to assess the accuracy of predictive simulations. Numerical modeling requires a complete protocol to be followed starting from establishing the purpose or objectives of modeling to conceptualization to model design to calibration, validation, predictions, sensitivity analysis and finally the post audit.

The recent concept of ground water management models are exclusively used to establish the safe limit for exploitation of ground water from different aquifer system including confined aquifer. The ground water management models basically operate on simulation - optimisation platform (SO Model) with an objective to arrive at the safest level of development without dropping the heads below given level at specified locations.

Data requirements for Analytical/ Numerical modeling

Ideally speaking, the data requirement for constructing a ground water flow / transport model requires all the parameters which constitute a groundwater flow equation at maximum number of points in space and time. However in real world situation it may not be possible to achieve this owing to various constraints including cost considerations. Hence, depending upon the objective of modeling and the accuracy desired the frequency of observation and the density of data requirement should be optimized. A good strategy is to start with a very simplified model with minimal data, carry out sensitivity analysis to identify critical data gaps and gradually refine the model through expanding the database. The data required for modeling may be grouped under two broad categories, the data pertaining to Physical framework of the system and data pertaining to hydrogeologic framework, the details of data requirement is listed below;

Physical Framework

- Geologic map and cross sections, fence diagrams showing the aquifer geometry and boundaries of the system
- Contour maps showing the elevations of the top and bottom of the aquifers to be modeled.
- Map showing the extent and thicknesses of the stream, rivers, drains and canals etc to be modeled.

Hydrogeologic Framework

- Water table and piezometric point data, maps, interpolated values etc. for all the aquifers under consideration to be used as initial piezometric heads.
- Historical water tables, piezometric heads surface water levels, discharges of streams etc.
- Maps and cross sections showing the distribution of hydraulic properties such as K, T.
- Maps and cross sections showing the storage properties such of the aquifers and confining beds.
- Hydraulic properties such as conductance for the surface water bodies, streams etc.
- Spatial and temporal variation of rates of evapotranspiration, groundwater recharge, groundwater pumpage etc.

The applicability of various methods for assessment of ground water resources in confined aquifers depends on scale of assessment, availability of hydraulic parameters and the purpose of the study. The storage concept and the rate concept methods are simpler and can be applied on a regional scale, if the required parameters pertaining to confined aquifers is available. The availability and development potential of ground water in confined aquifers can be approximated using these methods. In the rate concept, the volume of water flowing through a specified column in the specified time is approximately equal to the amount available for development during that period. In the storage concept, the volume of ground water available for development at a particular time can be approximated by lowering the piezometric heads to desired level.

4.2 Illustrative Examples:

In order to illustrate the various concepts and methods through model computations for assessment of potential of confined aquifers, studies were taken up in parts of Haryana & Punjab states. The study areas were selected in view of hydrogeologcial understanding and availability of input parameters. In the following paragraphs a brief on hydrogeological setting, sub-surface disposition of the aquifers and aquifer parameters is presented followed by model computations.

A. HARYANA

The area under study comprises of Yamunanagar, Kurukshetra, Karnal, Panipat, Sonipat and Faridabad districts of Haryana state. The exploratory drilling was carried out by CGWB upto 450 m. Four groups of permeable aquifers separated by three poorly permeable/impermeable horizons have been identified based on distinct aquifer characteristics, which are described in the following paragraphs.

Aquifer Group – I

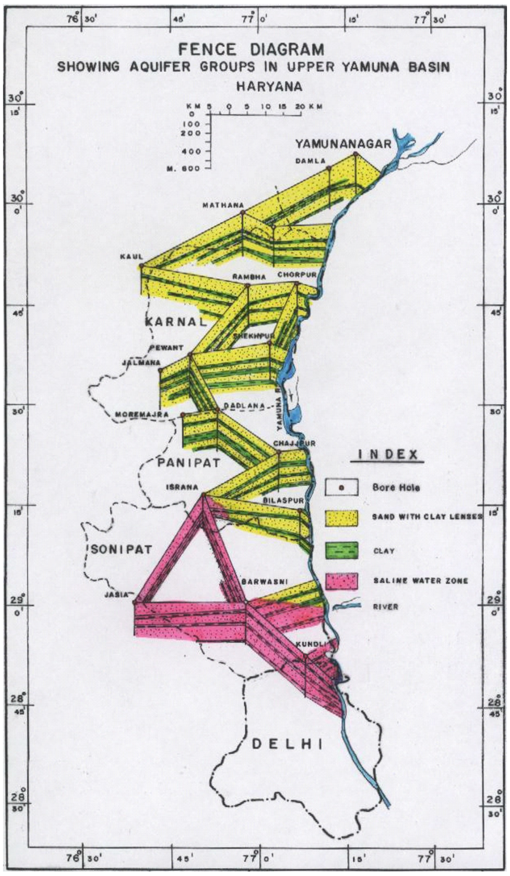
This aquifer group under water table conditions, extends from water table down to a maximum of 167 m below ground level and occurs all over the basin. This is composed of relatively coarse sediments. It is underlain by a clayey horizon 10 to 15 m thick, which is regionally extensive. The quality of water is fresh in the Northern parts of the basin than in Southern parts.

Aquifer Group – II

This aquifer group consisting of different sand and clay lenses occurs at variable depths ranging from 65 m to 283 m bgl. The sediments of this group are less coarse than sediments of aquifer – I and are admixed with kankar. The quality of water is reasonably fresh except in southwestern parts. The group is underlain by another clayey horizon, which is considerably thick at places and appears to be regionally extensive. This aquifer is under semi-confined to confined conditions
.

Aquifer Group – III

This group comprises of thin sand layers alternating with thicker clay layers and occurs at variable depths ranging between 197 m and 346 m bgl. The granular material of this group is generally finer in texture and more so in southern parts. This aquifer group is under confined conditions.



The aquifer parameters and characteristics of the confining layers of Aquifer Groups – I, II and III are given in following table.

TABLE: Aquifer Parameters of Aquifer Groups – I,II, III

	Aquifer group I		**Aquifer group II**		**Aquifer group III**	
Parameter	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
Transmissivity 'T' (m^2/day)	800 – 5210	2200	350 – 1050	700	345 – 830	525
Lateral hydraulic conductivity 'Kr' (m/day)	8.75 – 47.10	24.00	3.95 – 10.70	7.2	3.50 – 10.70	7.10
Storativity 'S'	2.10 – 24.00	12.00	5.60×10^{-4} - 1.70×10^{-3}	1.0×10^{-3}	6.60×10^{-4} - 2.40×10^{-4}	4.50×10^{-4}

Aquifer Group – IV

The aquifer – III is underlain by a thick clayey horizon, which in turn is underlain by another permeable granular horizon. This aquifer group has not been fully investigated. This aquifer is under confined conditions.

Sample computation - Haryana

The Ground water resources of deeper aquifers have been worked out on the basis of aquifer geometry as established. Reconciled Values of Sy, h0, h1 with the state government have been considered for sample computations

An attempt has been made to illustrate the assessment of ground water potential of confined aquifer using different concepts as discussed above through model computations. The aquifer properties of first confined aquifer consisting of different sand and clay lenses occurring at variable depths have been considered for these calculations. The average transmissivity (T) value of 700 m^2/day, average Lateral hydraulic conductivity (Kr) value of 7.2 m/day, average Storativity (S) value of $1.0 * 10^{-3}$ has been taken.

- *Computation using Flow rate Concept*

. Q = TIL
= T X δh/δl X L

T = 700 m^2/day
L = 40 km
(Length of flow – NW-SE face of study area)
δh = 10 m
δl = 8 km = 8000 m
Q = $700 * 10/ 8000 * 40 * 10^3$
= **$35 * 10^3$ m^3/day**

Thus, annual flow across NW-SE face of area using flow rate concept is
= $35 * 10^3 * 365$ **m^3/day**
= **13 mcm/yr**

- *Computation using storage Concept*

Typical sample calculations for assessment of ground water resources of first confined aquifer have been done using storage concept for the area having following characteristics.

Area		= 7714 sq. km
Storativity	(S)	= $1.0 * 10^{-3}$

Average thickness of the unconfined aquifer - 132 m.
Thickness of upper confining bed - 13 m.
Average depth of bottom of first confining layer
= 145 m (132+13)
Time averaged piezometric head of confined aquifer (h1)
= 16 m

Four different scenarios have been presented while pumping is done from first confined aquifer and it has been presumed that piezometric head is lowered by 1, 10, 20 and upto bottom of first confined layer.

<u>Scenario I – If pumping water level is lowered by 1 m</u>

i. Pumping water level (h0) = 17 m
ii. Del(h) =(h0- h1) = 17 -16= 1 m
iii. Ground water resource (Qp) = A * S * Del(h)
= 7714 * $1.0*10^{-3}$ * 1
= 7.7 MCM

<u>Scenario II – If pumping water level is lowered by 10 m</u>

i. Pumping water level (h0) = 26 m
ii. Del(h) =(h0- h1) = 26 -16= 10 m
iii. Ground water resource (Qp) = A * S * Del(h)
= 7714 * $1.0*10^{-3}$ * 10
= 77 MCM

<u>Scenario III – If pumping water level is lowered by 20 m</u>

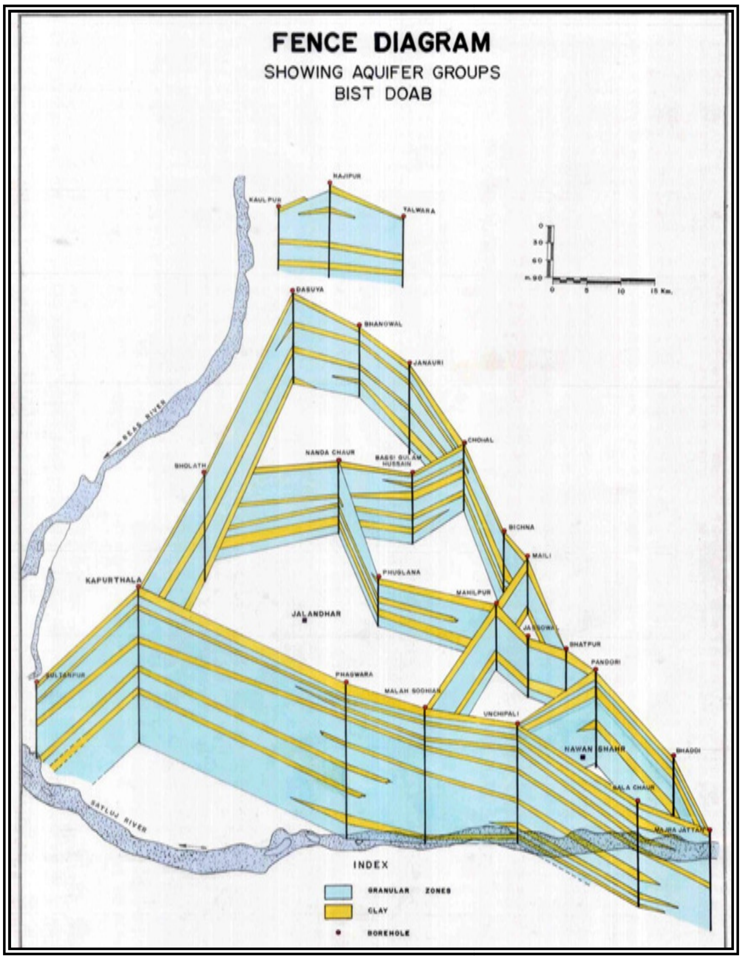
i. Pumping water level (h0) = 36 m
ii. Del(h) =(h0- h1) = 36 -16= 20 m
iii. Ground water resource (Qp) = A * S * Del(h)
= 7714 * $1.0*10^{-3}$ * 20
= 154 MCM

<u>Scenario-IV- If pumping water level is lowered upto the bottom of first confining layer</u>

i. Average depth of bottom of first confining layer
= 145 m
ii. Pumping water level (h0) = 145 m
iii. Del(h) =(h0- h1) = 145 -16= 129 m
iv. Ground water resource (Qp) = A * S * Del(h)
= 7714 * $1.0*10^{-3}$ * 129
= 995 MCM

B. PUNJAB

In Punjab Bist doab area lying between the Sutlej and Beas river and Siwalik ranges has been considered for the study. It comprises of Kapurthala, Jalandhar, Nawan shahar and Hoshiarpur districts and covers a total area of 8872 sq. km.



In the northeastern part of area sediments of recent origin are deposited in an area running parallel to the Himalayan range. This area is locally called Kandi and forms major recharge zone to the underlying aquifers in the lower reaches of the Bist-Doab. In this belt, ground water occurs mainly under unconfined conditions. Sand lenses interspersed with clay beds are predominant in the area. In the lower reaches sediments comprises mainly of fluvial origin. Main lithological units are sand and gravel horizons coupled with intercalating clay beds.

Aquifer geometry of the area has been worked out on the basis of ground water exploration done by CGWB and state government and presented in fence diagram (Fig…). The data of only those wells have been considered which are found to be representative of the area. Based on the various studies multi layered aquifer system in the area has been established, which is described as follows

Aquifer group I

The top layer of this aquifer group comprises of coarse sand beds, which are at places gravelly in nature. The sand beds are generally thick separated by small, thin clay beds that are not regionally extensive. In the northern part of the area thickness of clay beds and their occurrence increase substantially. This layer has varying thickness that ranges from 72m to 94m. The average thickness of this top layer is 72m in Hoshiarpur district, 76m in Nawanshahr district, 81m in

Jalandhar district and 94m in Kapurthala district. A regionally extensive clay layer with varying thickness from 16 to 32m separates this aquifer from underlying aquifer group II. This confining clay layer is only 16m thick in kapurthala district, 21m in Nawanshahr and around 24m in Jalandhar district. The thickness of this layer is maximum in Hoshiarpur district towards north where it is 32m thick. This layer generally acts as a confining layer though confining properties is not very much clear.

Aquifer Group II

This group comprises of alternating sequences of thin layers of sand and clay beds. Sediments of this aquifer group are chiefly sand, clay, gravel and occasional kankar. The sand beds are generally thick and are separated by thin clay beds. Clay beds are not regionally extensive and they normally pinch out. The aquifer thickness of this group below the confining layer upto 250m has also been worked out. It has been estimated that a thick aquifer having a thickness ranging between 81 m to 105m occur in the area. The thickness of aquifer material bearing fresh water sediments is 81m in Hoshiarpur district, 85m in Kapurthala district, 87m in Jalandhar district and 105m in Nawanshahr district. Though no pumping test data is available for exclusively determining the aquifer parameters of this group, it is estimated that S values of this aquifer group in the Bist-doab area ranges from 2.5×10^{-3} to 7.1×10^{-3} with an average value of 3.85×10^{-3}. These values have been determined on the basis of pumping tests data of wells tapping multiple aquifer groups.

Sample computation – Punjab

An attempt has been made to illustrate the assessment of ground water potential of confined aquifer using different concepts discussed above through model computations. The Ground water resources of deeper aquifers have been worked out on the basis of aquifer geometry as established. Reconciled Values of Sy, h0, h1 with the state government have been considered for sample computations.

The first confined aquifer consisting of different sand and clay lenses occurs at variable depths ranging from 65 m to 283 m below ground level (bgl). The average transmissivity (T) value of 2900 m^2/day, average storativity (S) value of $3.85 * 10^{-3}$ have been taken for sample computations.

- *Computation using Flow rate Concept*

. Q = TIL

= T X δh/δl X L

T = 2900 m^2/day

L = 90 km

(Length of flow – NW-SE face of Bist-Doab)

δh = 10 m
δl = 6 km = 6000 m
Q = 2900 * 10/ 6000 * 90 * 10^3
= **43.47 * 10^4 m^3/day**

Thus, annual flow across NW-SE face of area using flow rate concept is

= 43.47 * 10^4 * 365
= 15877.5 * 10^4 m^3/yr
= **159 mcm /yr**

- *Computation using storage Concept*

Typical sample calculations for assessment of ground water resources of first confined aquifer have been done using storage concept for the area having following characteristics.

Area (A) = 6200 sq. km
Storatvity (S) = 3.85 * 10^{-3}
Average thickness of the unconfined aquifer - 107 m.
Thickness of upper confining bed - 24 m.
Average depth of bottom of first confining layer
h_o = 131 m bgl (107 + 24)
Time averaged post monsoon piezometric head
h_1 = 13 m bgl

Four different scenarios have been presented while pumping is done from first confined aquifer and it has been presumed that piezometric head is lowered by 1, 10, 20 and upto bottom of first confined layer.

Scenario I – If pumping water level is lowered by 1 m

i. Pumping water level (h0) = 14 m
ii. Del(h) =(h0- h1) = 14 -13= 1 m
iii. Ground water resource (Qp) = A * S * Del(h)
= 6200 * 3.85*10^{-3} *
= 24 MCM

Scenario II – If pumping water level is lowered by 10 m

i. Pumping water level (h0) = 23 m
ii. Del(h) =(h0- h1) = 23 -13= 10 m
iii. Ground water resource (Qp) = A * S * Del(h)
= 6200 * 3.85*10^{-3} * 10
= 240 MCM

Scenario III – If pumping water level is lowered by 20 m

i.	Pumping water level (h0)	= 33 m
ii.	Del(h) =(h0- h1)	= 33 -13= 20 m
iii.	Ground water resource (Qp)	= A * S * Del(h)
		= 6200 * 3.85*10^{-3} * 20
		= 480 MCM

Scenario-IV- If pumping water level is lowered upto the bottom of first confined aquifer

i.	Average depth of bottom of first confining layer	
		= 131 m
ii.	Pumping water level (h0)	= 131 m
iii.	Del(h) =(h0- h1)	= 131 -13= 118 m
iv.	Ground water resource (Qp)	= A * S * Del(h)
		= 6200 * 3.85*10^{-3} * 118
		= 2817 MCM

CHAPTER 5

Recommendations

- The assessment of ground water availability and development potential of deeper aquifer would require detailed mapping of the aquifer systems to establish the aquifer geometry including delineation of recharge areas of the confined aquifers and estimation of aquifer parameters. **Therefore it is recommended that regional aquifer mapping and establishing aquifer geometry / parameters of the individual aquifers needs to be undertaken for the entire country.**

- There should a well established mechanism for **monitoring of water level / piezometric heads** with optimal network density and frequency for different aquifers.

- The ***preliminary estimate*** of the availability and development potential of ground water in confined aquifers can be attempted using simplistic approach of **flow rate concept** and **storage concept**. However, for the purpose of ***planning ground water development*** of confined aquifers, precise assessment of availability and their development potential need to be ascertained by **ground water modeling approach**.

- A **pilot study** may be taken up in selected part of the upper Yamuna basin in Haryana state, following the recommended methods including development of an operational model using numerical approach for assessment of ground water availability in space and time and the development potential of deeper aquifer.

- The resources of deeper confined aquifer can be harnessed keeping in view the long term **sustainability of the aquifer**. An essential consideration in development of confined aquifer is the **chemical quality** of water. The primary management tool for ground water developmnt in confined aquifer is well spacing, restriction on the rate of withdrawal from the aquifer.

- It is recommended that the **ground water availability and potential in confined aquifers need to be assessed in a scientific way** before planning for its development keeping in view the adverse consequences of over-development of confined aquifers.

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ANEEXURE 1

CENTRAL GROUND WATER BOARD
MINISTRY OF WATER RESOURCES

3-8/CGWB/M(SAM)/2005 Dated 24.10.05

The Annual Replenishable Ground Water Resources of the country have been assessed using GEC'97 methodology. In addition to the Annual Replenishable Ground Water Resources in the active recharge zone, there exists a huge ground water resource in the deeper parts of the unconfined aquifers and also in the deeper confined aquifers in the areas covered by alluvial sediments. In order to develop a methodology for assessing the development potential of deeper aquifers, a Working Group is hereby constituted with the following composition.

1.	Member (SAM), CGWB	Chairman
2.	Chief General Manager, NABARD	Member
3.	Representative from Ground Water Cell, Directorate of Agriculture, Govt. of Haryana	Member
4.	Representative from Water Resources & Environment Directorate, Irrigation Department, Punjab	Member
5.	Representative from State Ground Water, Department, Uttar Pradesh	Member
6.	Scientist, CGWB	Member
7.	Scientist, CGWB	Member Secretary

The terms of references of the Working Group will be as follows –

4 To review the scientific studies carried out with respect to the confined (deeper) aquifer.
5 To suggest suitable methodology to assess the development potential of deeper aquifers.
6 To review the status of utilization of deeper aquifer.
7 Any other aspect relevant to the terms referred above.

The Working Group would submit its report to the R&D Advisory Committee on Ground Water Estimation within three months after constitution of the Working Group.

Sd/-
(Dr. Saleem Romani)
Chairman, CGWB

Copy to:

1. Member (SAM), Central Ground Water Board, Bhujal Bhawan, NH-IV, Faridabad. He is requested to include two scientists from CGWB as Member and Member Secretary of the Working Group.
2. Chief General Manager, NABARD, Plot No. C-24, G-Block, Bandra-Kurla Complex, Post Box No. 8121, Bandra (East), Mumbai – 400051.
3. Director, Agriculture Deptt., (Ground Water Cell), Govt. of Haryana, Sinchai Bhawan, Sector – 5, Panchkula – 134112.
4. The Director, Water Resources & Environment Directorate, Government of Punjab, SCO- 32-34, Sector-17C, Chandigarh.- 160017.
5. The Director, Ground Water Department, UP, Government of Uttar Pradesh, 9th Floor, Indira Bhavan, Ashok Marg, Lucknow – 226001.

Sd/-
(Dr. Saleem Romani)
Chairman, CGWB

Copy also forwarded for information to:

Commissioner (GW), Ministry of Water Resources, Shram Shakti Bhawan, New Delhi.

Sd/-
(Dr. Saleem Romani)
Chairman, CGWB

CENTRAL GROUND WATER BOARD
MINISTRY OF WATER RESOURCES

3-8/CGWB/M(SAM)/2005 Dated 11.11.05

The following officers from CGWB are included in the Working Group to develop a methodology for assessing the development potential of deeper aquifer.

1.	S.K. Sinha, Scientist ‘C’, CGWB	Member
2.	Rana Chatterjee, Scientist ‘D’, CGWB	Member Secretary

The terms of references of the Working Group are as follows –

1. To review the scientific studies carried out with respect to the confined (deeper) aquifer.
2. To suggest suitable methodology to assess the development potential of deeper aquifers.
3. To review the status of utilization of deeper aquifer.
4. Any other aspect relevant to the terms referred above.

The Working Group would submit its report to the R&D Advisory Committee on Ground Water Estimation within three months after constitution of the Working Group.

Sd/-
(B.M. Jha)
Member (SAM)

Copy for information to:

1. Chief General Manager, NABARD, Plot No. C-24, G-Block, Bandra-Kurla Complex, Post Box No. 8121, Bandra (East), Mumbai – 400051.
2. Director, Agriculture Deptt., (Ground Water Cell), Govt. of Haryana, Sinchai Bhawan, Sector – 5, Panchkula – 134112.
3. The Director, Water Resources & Environment Directorate, Government of Punjab, SCO- 32-34, Sector-17C, Chandigarh.- 160017.
4. The Director, Ground Water Department, UP, Government of Uttar Pradesh, 9th Floor, Indira Bhavan, Ashok Marg, Lucknow – 226001.

Sd/-
(B.M. Jha)
Member (SAM)

3-8(1)/RES/CGWB/M(SAM)/2009-
CENTRAL GROUND WATER BOARD

Dated 21.04.09

In order to finalize the report of the working group on suggesting a methodology for assessing the development potential of deeper aquifer, a sub-committee consisting following officers is hereby constituted -

1. Sanjay Marwah, Scientist ‘D’, CGWB, NWR, Chandigarh
2. Rana Chatterjee, Scientist ‘D’, CGWB, New Delhi
3. S. K. Sinha, Scientist 'D', CGWB, Faridabad

The sub-committee would submit its report to the Working Group by 15.06.09.

Sd/-
(A.R. Bhaisare)
Member (SAM)

Distribution:

1. Chief General Manager, NABARD, Plot No. C-24, G-Block, Bandra-Kurla Complex, Post Box No. 8121, Bandra (East), Mumbai – 400051.
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3. The Director, Water Resources & Environment Directorate, Government of Punjab, SCO- 32-34, Sector-17C, Chandigarh- 160017.
4. The Director, Ground Water Department, UP, Government of Uttar Pradesh, 9th Floor, Indira Bhavan, Ashok Marg, Lucknow – 226001.
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7. TS to Chairman, CGWB, Faridabad
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9. Rana Chatterjee, Scientist 'D', CGWB, New Delhi
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Annexure – 2

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